Cognitive models of memory processes in sentence comprehension: A case study using Bayesian hierarchical modeling

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How can we evaluate (slightly) different theories?

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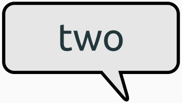
By implementing the theories as ***computational models*** using ***Bayesian methods*** and ***comparing the models***.

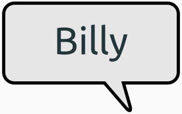
The


two

scouts


who

ditched


Billy

and

Weary


were

shot.

Who was shot?

Who was shot?

The <u>two scouts</u> who ditched Billy and Weary were shot.

Who was shot?

The two scouts who ditched Billy and Weary were shot.

Who was shot?

The two scouts who ditched Billy and Weary **were** shot.


The two scouts who
ditched Billy and Weary
were
were

Models of memory in sentence processing

Cue-based retrieval mechanism

Models that assume a cue-based retrieval mechanism:

(I) Activation-based model (Lewis and Vasishth 2005)

(II) Direct-access model (McElree 2000)

Cue-based retrieval mechanism

Models that assume a cue-based retrieval mechanism:

(I) Activation-based model (Lewis and Vasishth 2005)

(II) Direct-access model (McElree 2000)

Similar but not quite the same

(I) Activation-based model

based on ACT-R (Anderson and Reder 1999)

(I) Activation-based model

based on ACT-R (Anderson and Reder 1999)

Words in memory have an activation level, which

- depends on the match with the retrieval cues
- is noisy

The highest activation determines

- which word is retrieved
- the retrieval time ($\propto e^{-A}$)

(II) Direct-access model

The retrieval of a word in memory

- depends on the match with the retrieval cues
- can be repaired in case of error

- Access time is unaffected by the degree of match (i.e. direct access)
- Final processing time may be inflated by reanalyzed errors

(I) Activation-based model

match $\rightarrow$ activation $\rightarrow$ accuracy & RT

(II) Direct-access model

match $\rightarrow$ probability $\rightarrow$ accuracy $\rightarrow$ RT

Computational implementation

Benefits

- The general advantages of Bayesian inference: credible intervals, and flexibility in fitting complex non-linear models.
- A hierarchical structure means that both between- and within-group variances into account and pool information via shrinkage.

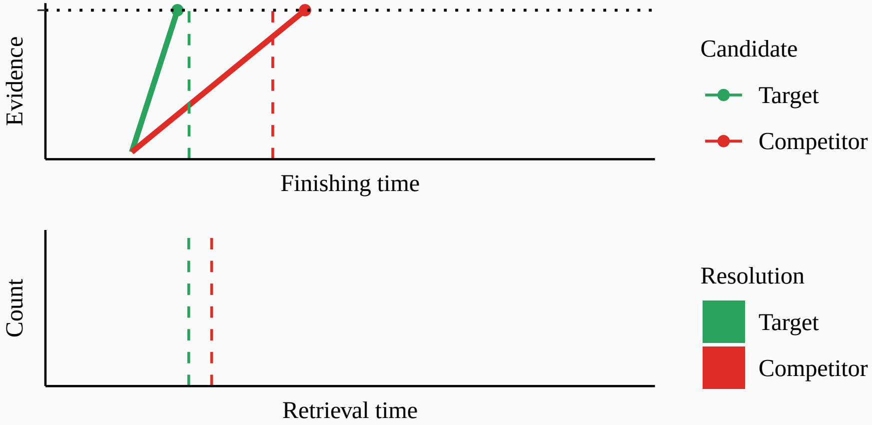
Computational modeling - Study

Nicenboim and Vasishth (2018) “Models of Retrieval in Sentence Comprehension: A computational evaluation using Bayesian hierarchical modeling”

- Implementation as Bayesian hierarchical models in Stan
- Data (from Nicenboim et al. 2018):
    - reading times at the verb
    - responses (multiple choice)
- Model comparison:
    - posterior predictive checking
    - k-fold cross validation

The activation-based model is a **race model**

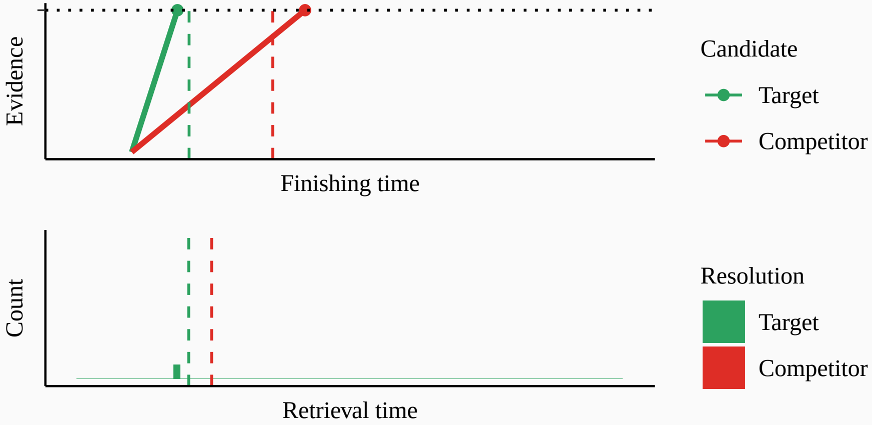
Trial 1



Computational modeling - (I) Activation-based model

The activation-based model is a **race model**

Trial 1



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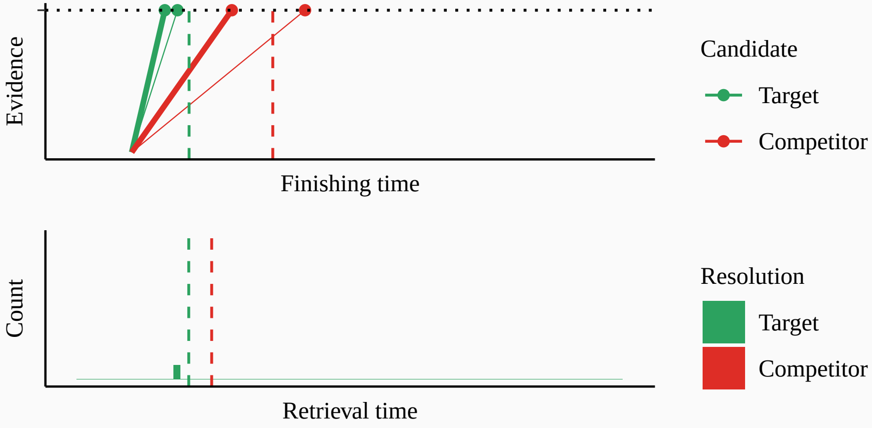

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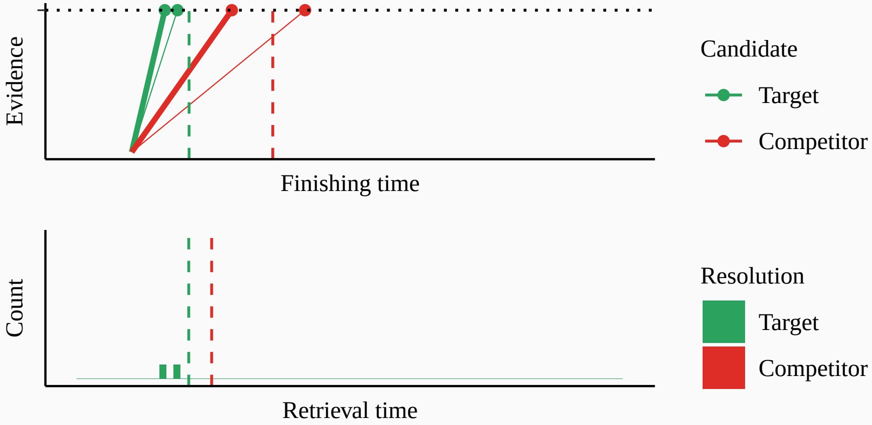

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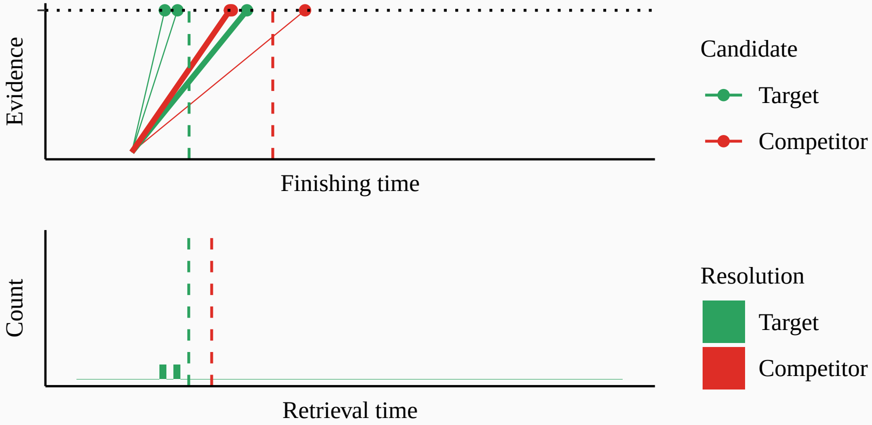

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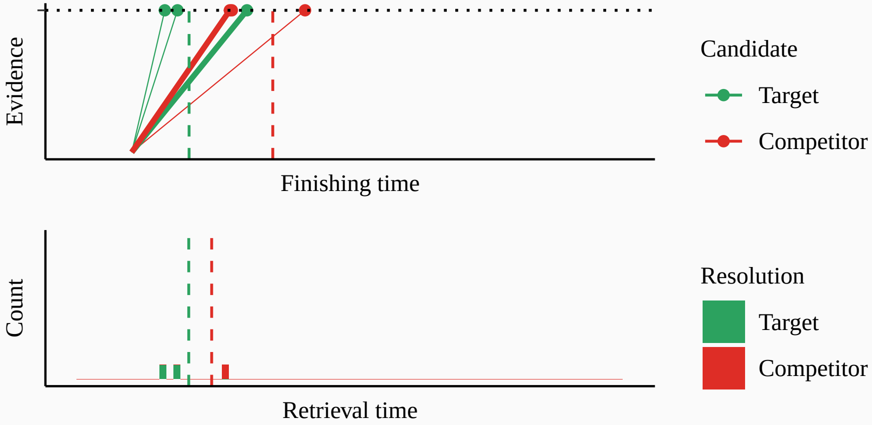

Computational modeling - (I) Activation-based model

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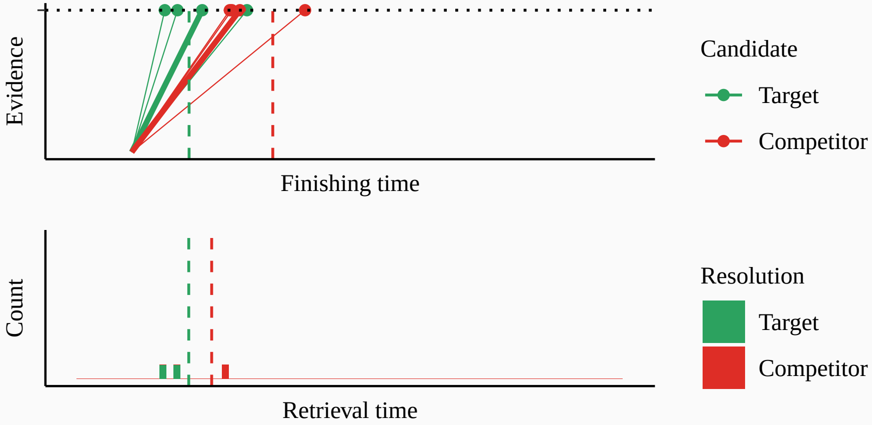
Trial 4



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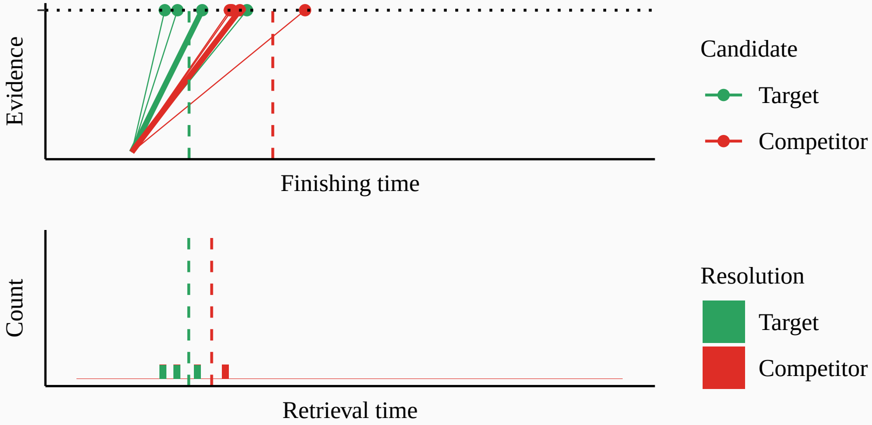

Computational modeling - (I) Activation-based model

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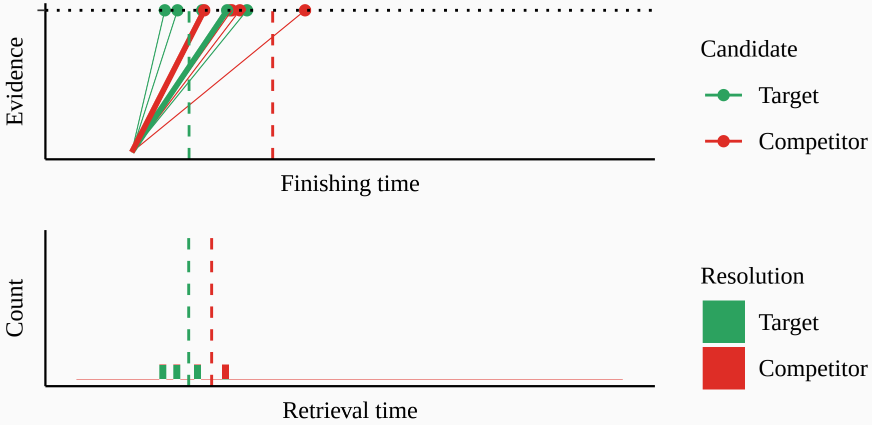
Trial 5



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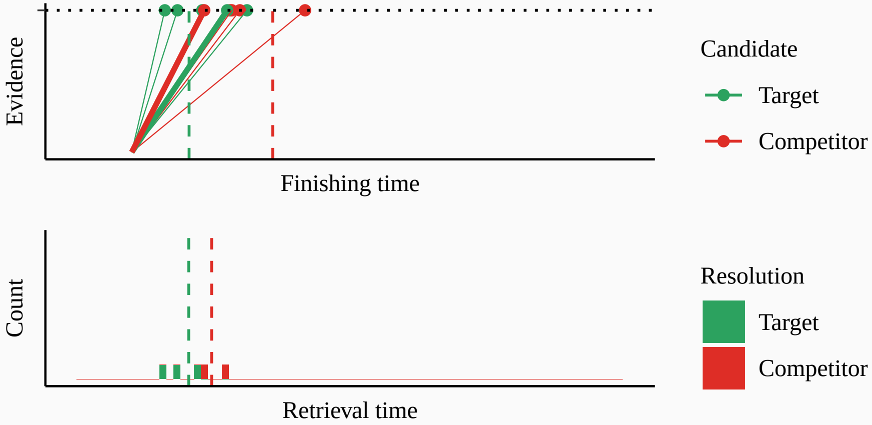

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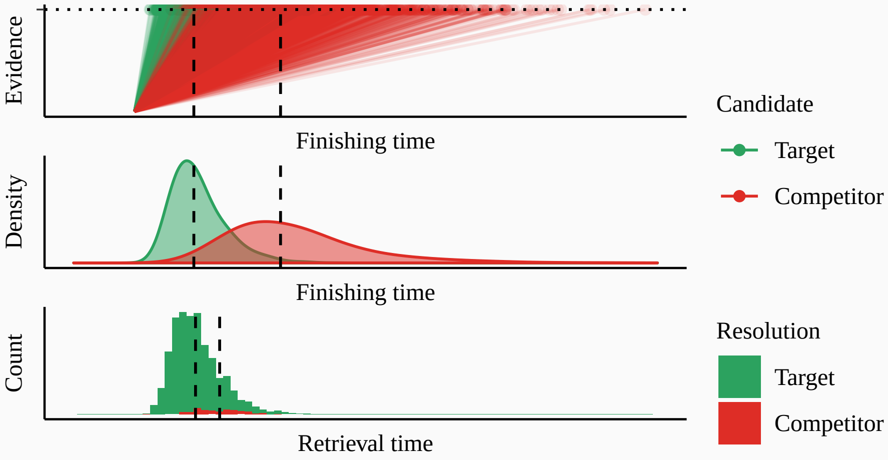


Computational modeling - (I) Activation-based model

$$Latency \propto e^{-\arg\max_c (A_c)} \tag{1}$$

$$t_c \propto e^{-A_c} \tag{2}$$

where $A_c \sim Normal(\mu_c, \sigma)$

Computational modeling - (I) Activation-based model

$$Latency \propto e^{-\arg\max_{c}(A_c)} \tag{1}$$

$$t_c \propto e^{-A_c} \tag{2}$$

$$\text{where } A_c \sim Normal(\mu_c, \sigma)$$

$$t_c \sim exp(Normal(\overbrace{b}^{\text{threshold}} - \overbrace{\mu_c}^{\text{av. rate}} + \overbrace{\mu_c}^{\text{other processes}}, \sigma)) \tag{3}$$

$$t_c \sim LogNormal(b - \alpha_c, \sigma) \tag{4}$$

$$t_{\text{other}} > t_{\text{selected}} \tag{5}$$

Computational modeling - (I) Activation-based model

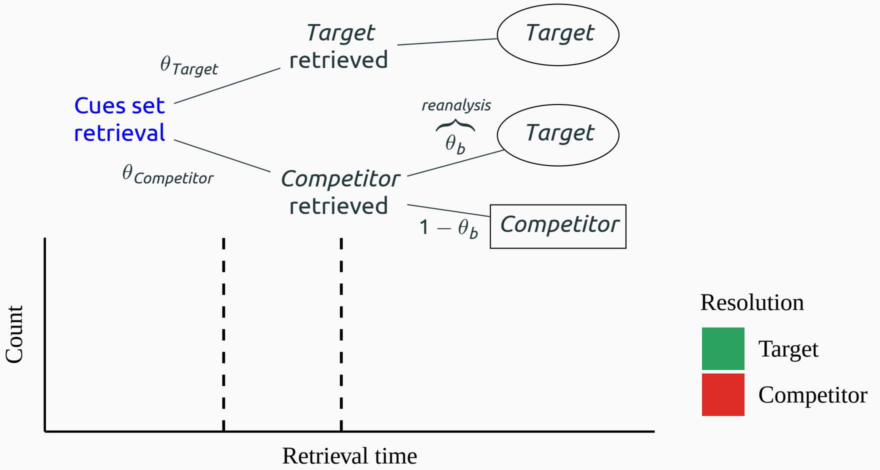
$$\overbrace{RT_{l,i,j}}^{\text{obs. time}} \sim \overbrace{\psi_i}^{\text{peripherial proc.}} + LogNormal(b - \alpha_{l,i,j,\text{selected}}, \sigma) \quad (6)$$

$$Pr[t_{\text{other}} > t_{\text{selected}}] = \int_{t_{\text{selected}}}^{\infty} LogNormal(t_{\text{other}} | b - \alpha_{\text{other}}, \sigma) \cdot dt_{\text{other}} \quad (7)$$

$$= 1 - \Phi\left(\frac{log(t_{\text{selected}}) - (b - \alpha_{\text{other}})}{\sigma}\right) \quad (8)$$

The direct-access model is a **mixture model**

Trial 1



Computational modeling - (II) Direct-access model

The direct-access model is a **mixture model**

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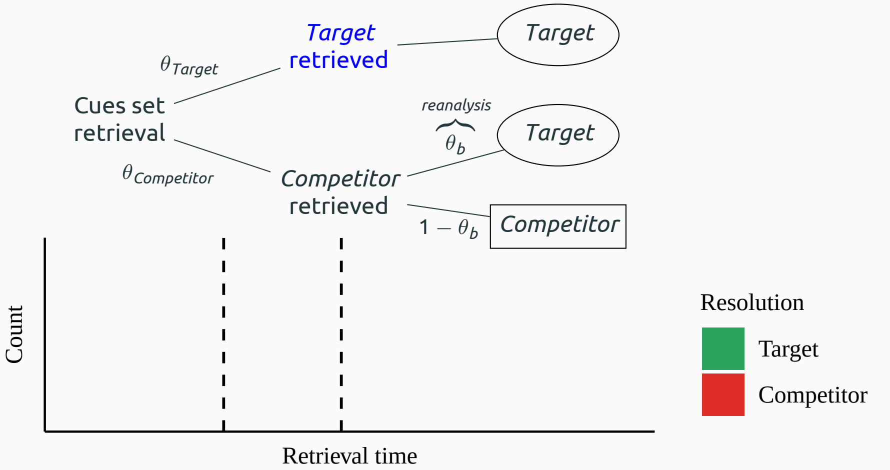

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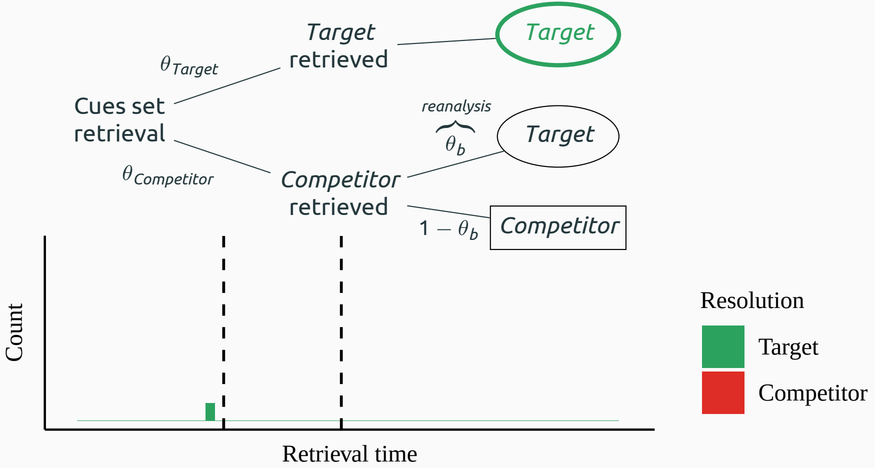

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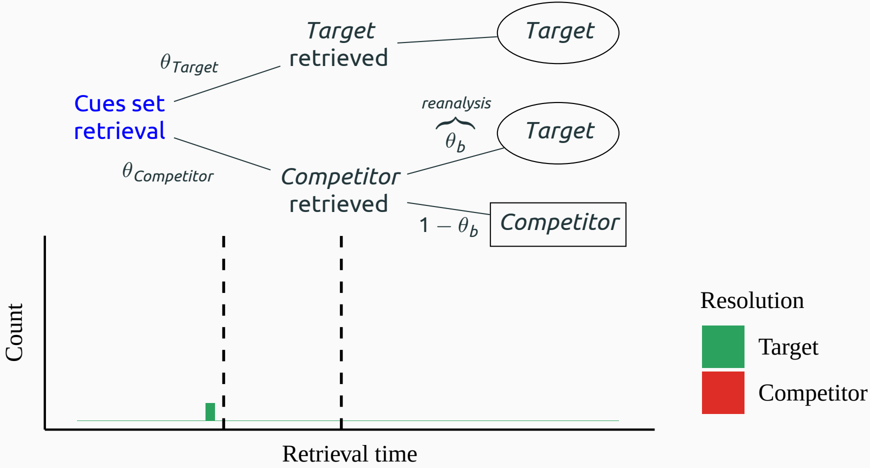

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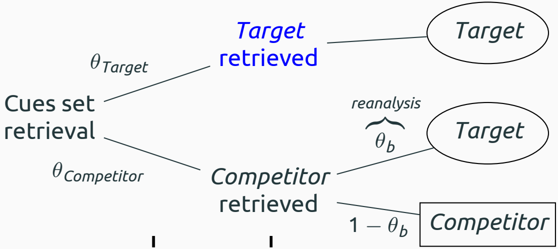

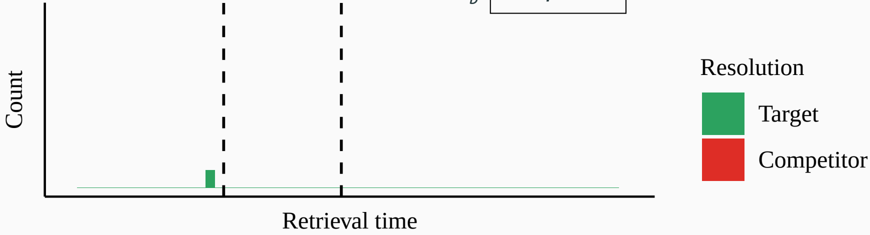

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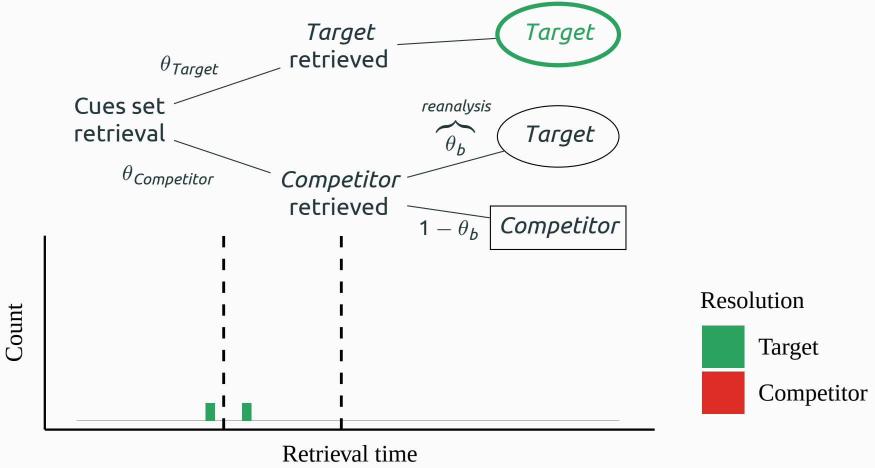

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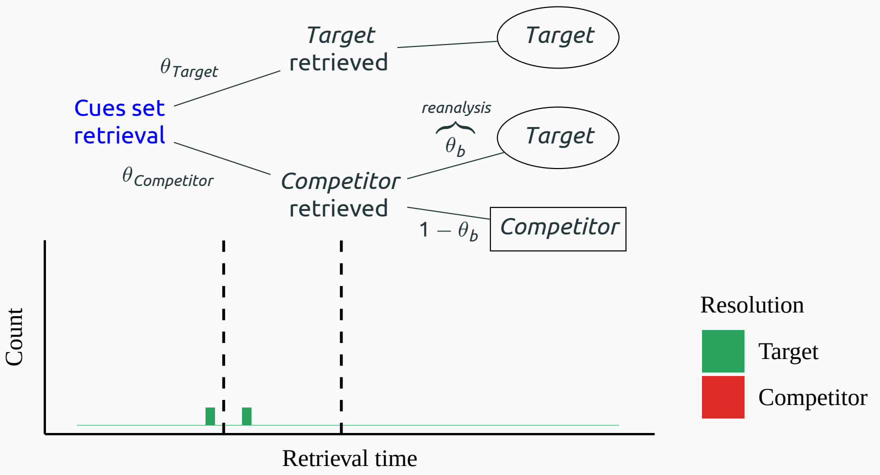

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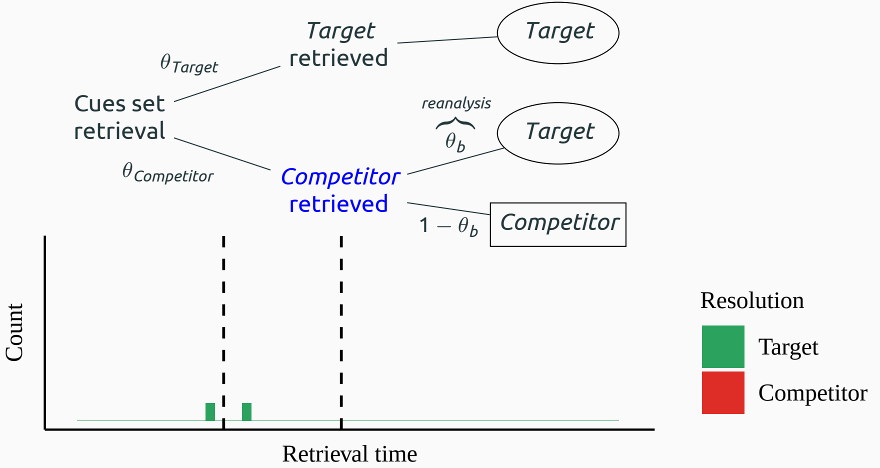

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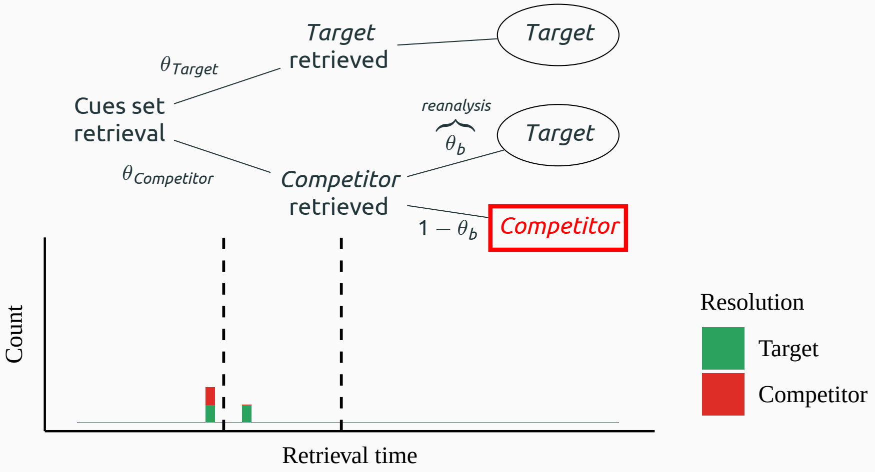

Computational modeling - (II) Direct-access model

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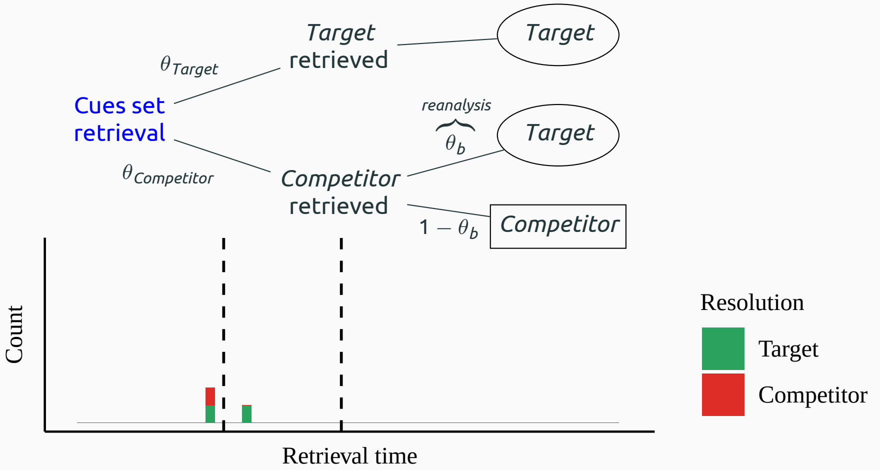

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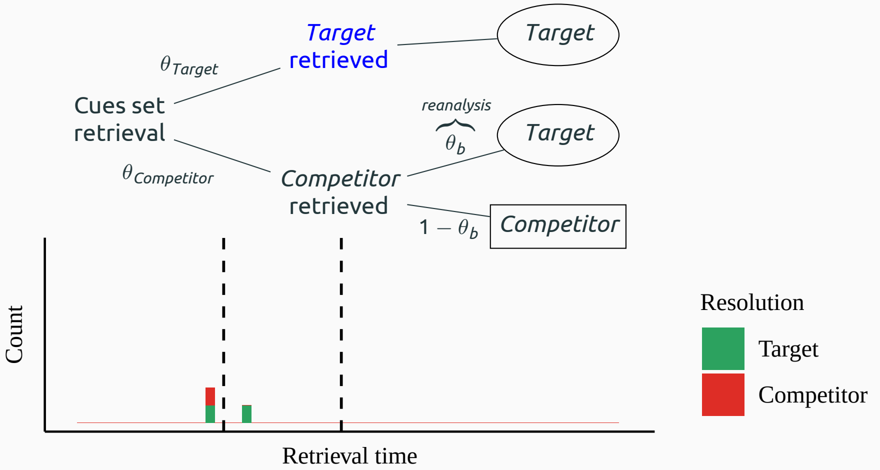

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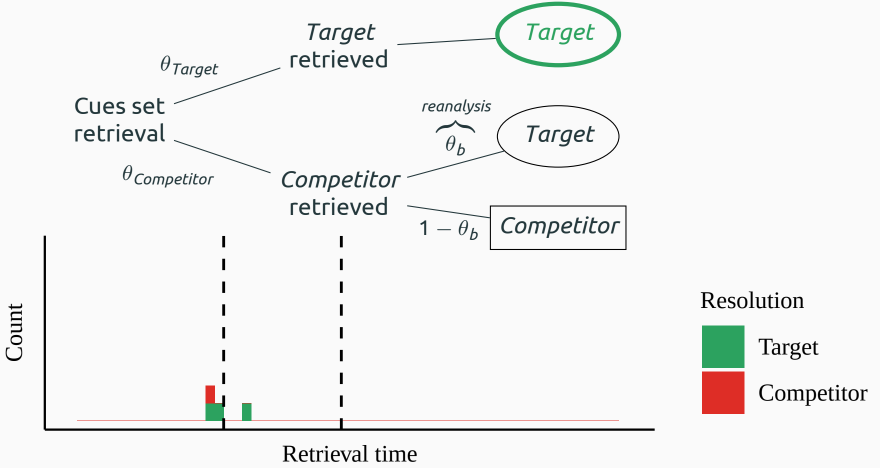

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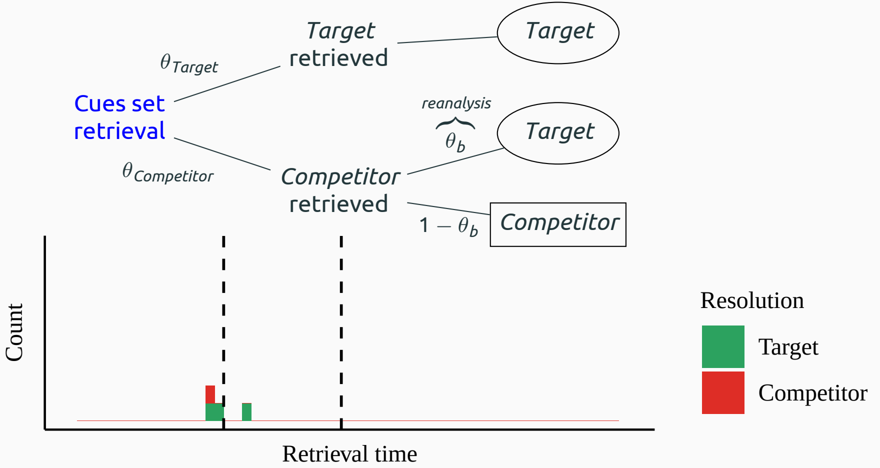

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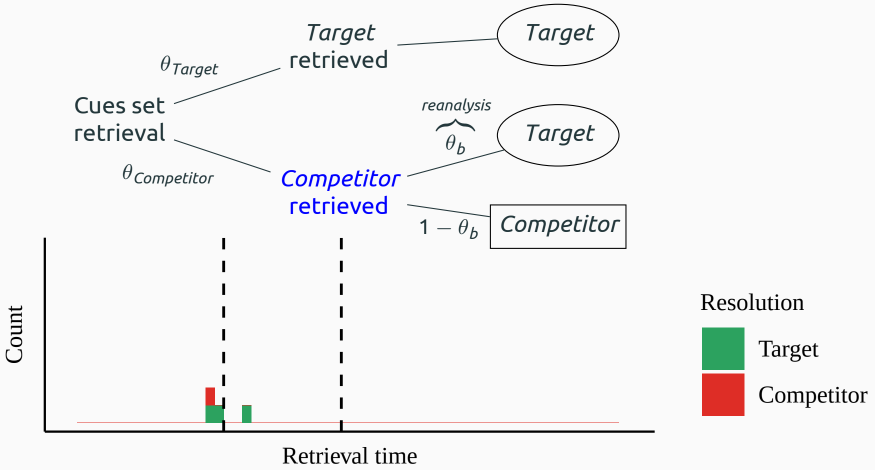

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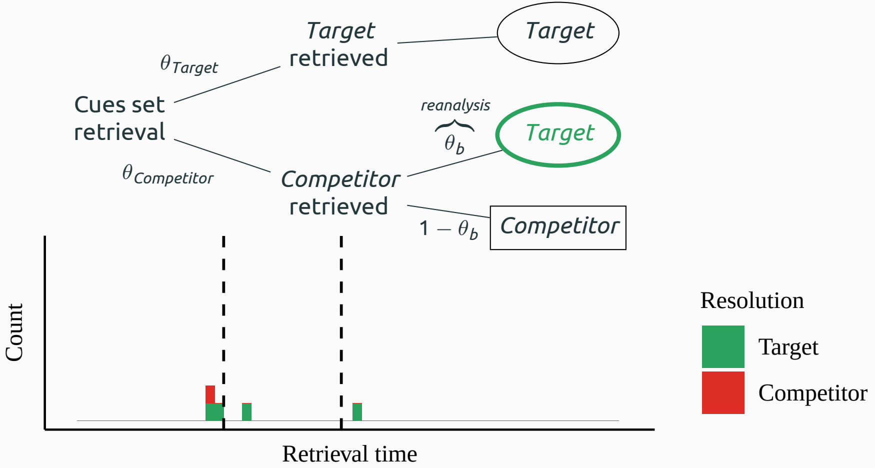

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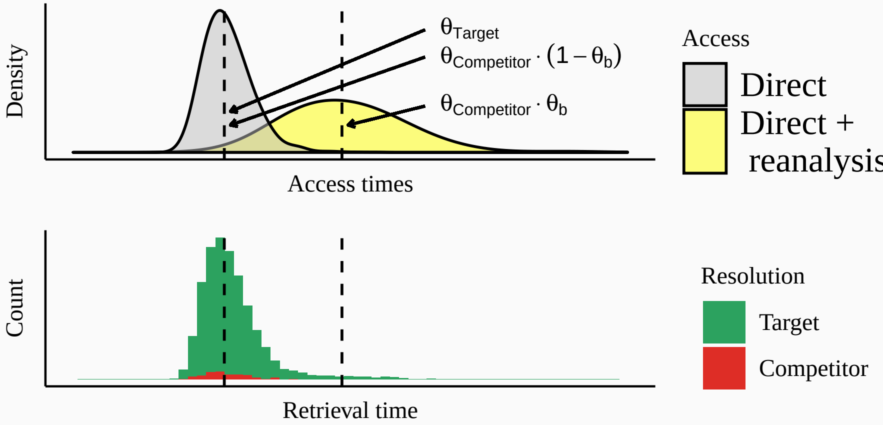

Computational modeling - (II) Direct-access model

$$P_r(Target) = \theta_{Target} + (1 - \theta_{Target}) \cdot \theta_b \tag{9}$$

$$P_r(Competitor_c) = \theta_{Competitor_c} \cdot (1 - \theta_b) \tag{10}$$

Computational modeling - (II) Direct-access model

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$$P_r(Competitor_c) = \theta_{Competitor_c} \cdot (1 - \theta_b) \tag{10}$$

$$RT_{Target,l,i,j} \sim \psi_i + \begin{cases} LogNormal(t_{da,i,j} + \gamma_{i,j}, \sigma) & \text{, if the first try is correct} \\ LogNormal(t_{da,i,j} + t_{b,i,j} + \gamma_{i,j}, \sigma) & \text{, otherwise} \end{cases} \tag{11}$$

$$RT_{Competitor_c,l,i,j} \sim \psi_i + LogNormal(t_{da,i,j} + \gamma_{i,j}, \sigma) \tag{12}$$

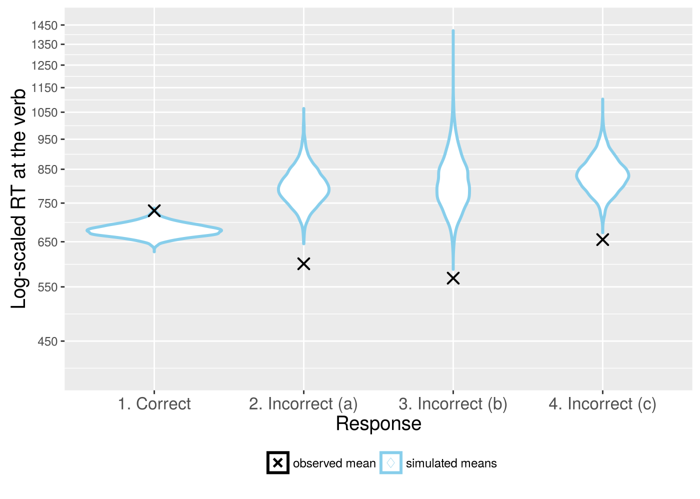
Some necessary assumptions for both models

- reading times at the verb $\rightarrow$ retrieval times
- responses (multiple choice) $\rightarrow$ word retrieved from memory at the verb

Model comparison

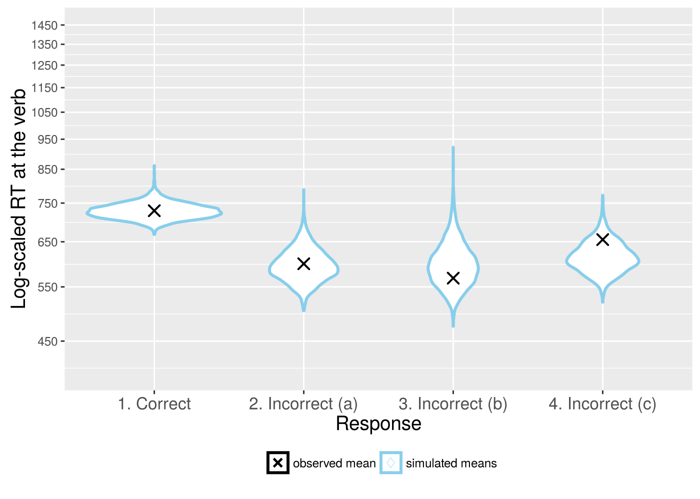
Model fit - Posterior predictive checks

(I) Activation-based model

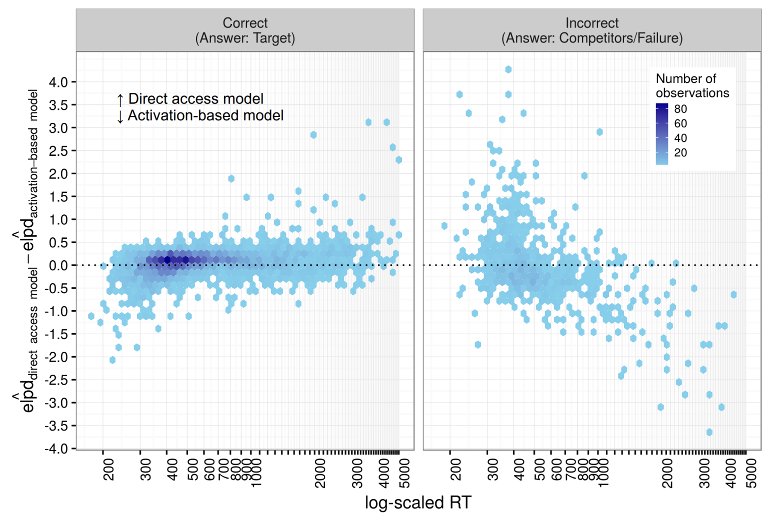


Model fit - Posterior predictive checks

(II) Direct-access model



Predictive accuracy - Model comparison with K-fold-CV



Discussion

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- Activation-based model fails to account for some aspects of the data.
- Direct-access model fits and predicts better the data.
- This has implication for the relationship between sentence processing and our memory system.
- We can understand where the activation-based model fails, and improve it (and we did that too...).

Discussion

Is the direct access to items in memory the only possibility?

Discussion

Possible improvements to the activation-based model

- add reanalysis (mixture in correct responses) to the activation-based model
- other models that assume the sequential sampling of evidence as a model of retrieval
- activation-based model with different variances (Brown and Heathcote 2008; Gillund and Shiffrin 1984)

Discussion

Possible improvements to the activation-based model

- add reanalysis (mixture in correct responses) to the activation-based model
- other models that assume the sequential sampling of evidence as a model of retrieval
- **activation-based model with different variances (Brown and Heathcote 2008; Gillund and Shiffrin 1984)**

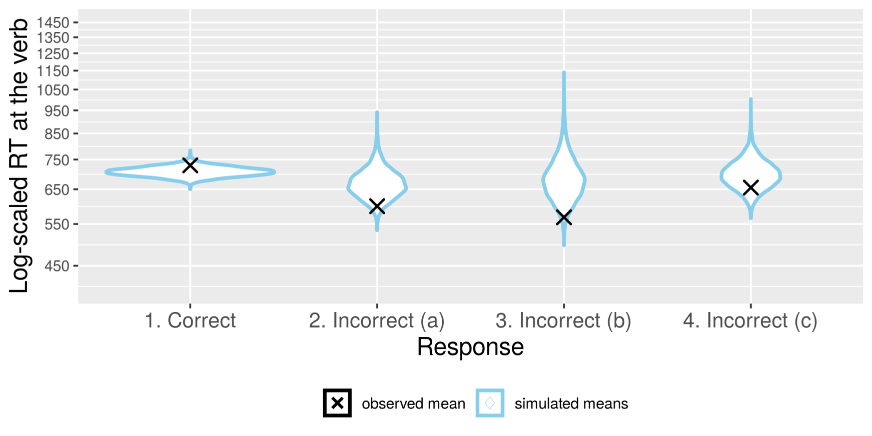
(III) Activation-based model with different variances

- item with highest total activation is retrieved, and its retrieval time depends on its total activation ($\propto e^{-A}$)
- **the noise in the activation depends on the match**

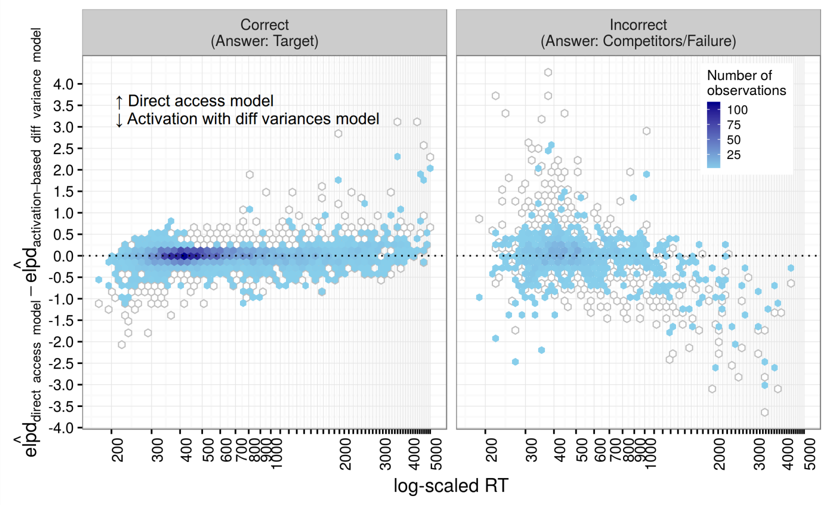
More model comparison

Model fit - Posterior predictive checks

(III) Activation-based model with different variances



Predictive accuracy - Model comparison with K-fold-CV



Discussion

Discussion

Both models are similarly good (or bad)

- The posterior predictive checks show a tighter fit for the direct access model (the $\times$'s are pretty much in the middle)
- The estimates of predictive accuracy are very similar
- The direct access model may be overfitting more, while the activation model with different variance may not be flexible enough

Conclusions

Summary

- Comparison of the activation-based model and the direct access model
- Incorrect retrievals were fast, which is incompatible with the (default) activation-based model
- The direct access model provides a better fit than the default activation-based model
- Race models (sequential sampling framework) could still be useful to explain retrieval
- A lognormal race with a different variances fits the data as well as the direct access model

Appendix

Nicenboim et al. (2018) - Stimuli

(1) a. High Interference

Der	**Wohltäter**,	der	den
The.sg.nom	**philanthropist**,	who.sg.nom	the.sg.acc

Assistenten		des	Direktors	**begrüßt**	**hatte**,	saß
assistant	(of)	the.sg.gen	director	**greeted**	**had.sg**,	sat.sg

später	im		Spendenausschuss.
later	in	the	donations committee.

'The philanthropist, who had greeted the assistant of the director, sat later in the donations committee.'

b. Low Interference

Der	**Wohltäter**,	der	die
The.sg.nom	**philanthropist**,	who.sg.nom	the.pl.acc

Assistenten		der	Direktoren	**begrüßt**	**hatte**,	saß
assistants	(of)	the.pl.gen	directors	**greeted**	**had.sg**,	sat.sg

später	im		Spendenausschuss.
later	in	the	donations committee.

'The philanthropist, who had greeted the assistants of the directors, sat later in the donations committee.'

Nicenboim et al. (2018)

(2) Wer hatte jemanden begrüßt?

Who had greeted someone?

a. der/die Wohltäter

the philanthropist(s) (correct)

b. der/die Assistent/en

the assistant(s)

c. der/die Direktor/en

the director(s)

d. Ich weiß es nicht

I don’t know